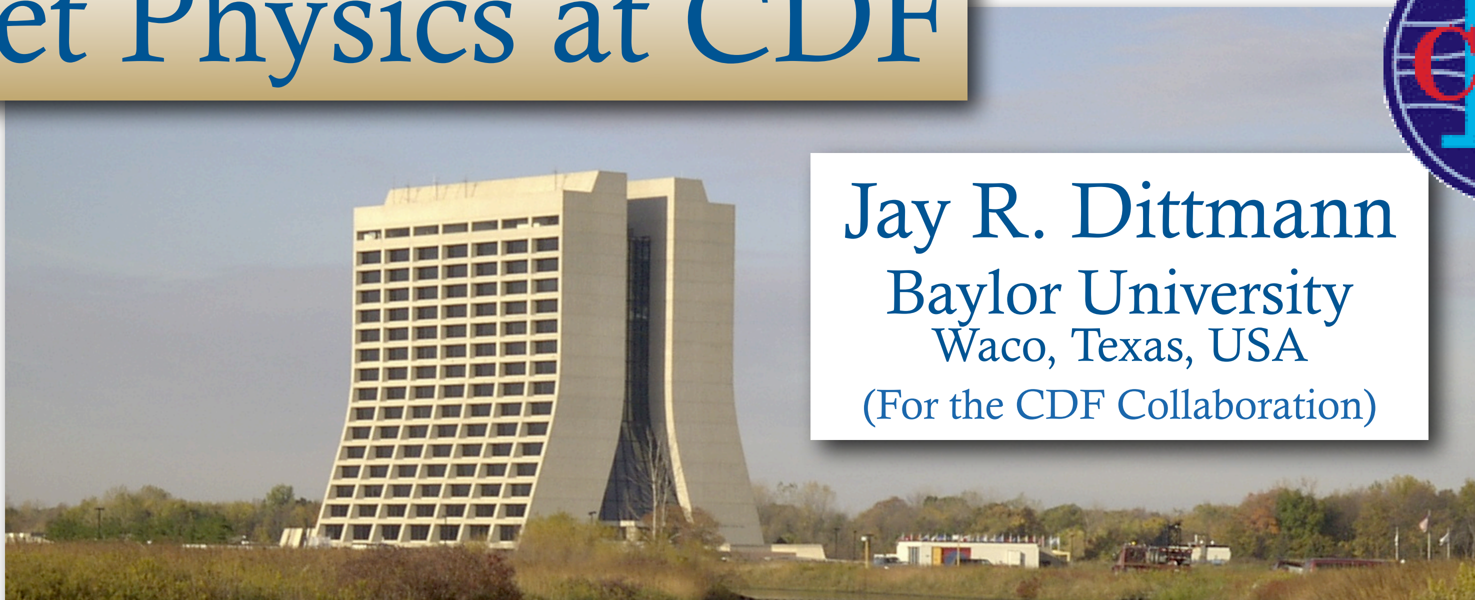
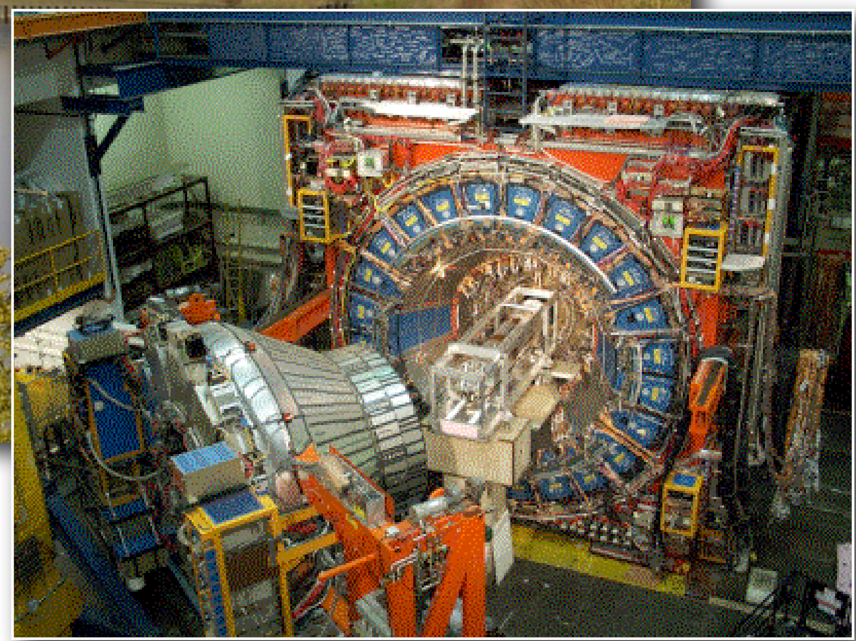
Jet Physics at CDF



Jay R. Dittmann
Baylor University
Waco, Texas, USA
(For the CDF Collaboration)



Workshop on Low x Physics
Helsinki, Finland   Sept 1, 2007

Outline

- Overview
  - Jet Production
  - Jet Algorithms at CDF
  - The Fermilab Tevatron
  - The CDF Detector
- Measurements
  - Inclusive Jet Cross Section (Midpoint)
  - Inclusive Jet Cross Section (k_T)
  - Dijet Production
  - *b*-jet Production
  - $b\bar{b}$ Dijet Production
  - Vector Boson + Jets Production
    - W + Jets
    - Z + Jets
    - W + $b\bar{b}$
    - Z + *b* Jets
    - W + charm
- Conclusions

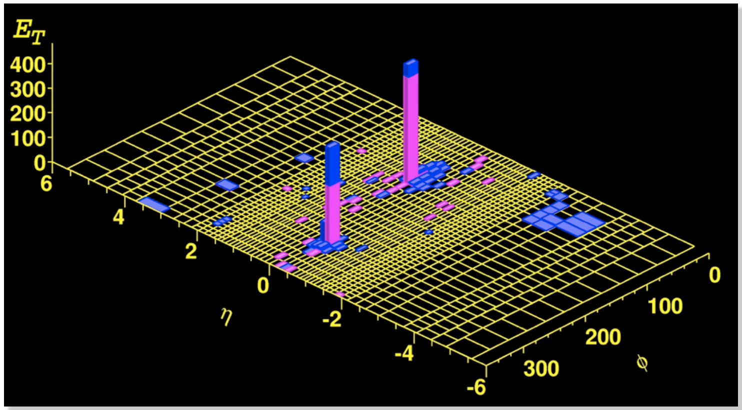
QCD Physics at the Fermilab Tevatron

- The Fermilab Tevatron Collider serves as an arena for precision tests of QCD with jets, W/Z bosons, and photons
  - Highest Q^2 scales currently achievable (searches for new physics at small distance scales)
  - Sensitivity to parton distributions over a broad kinematic range

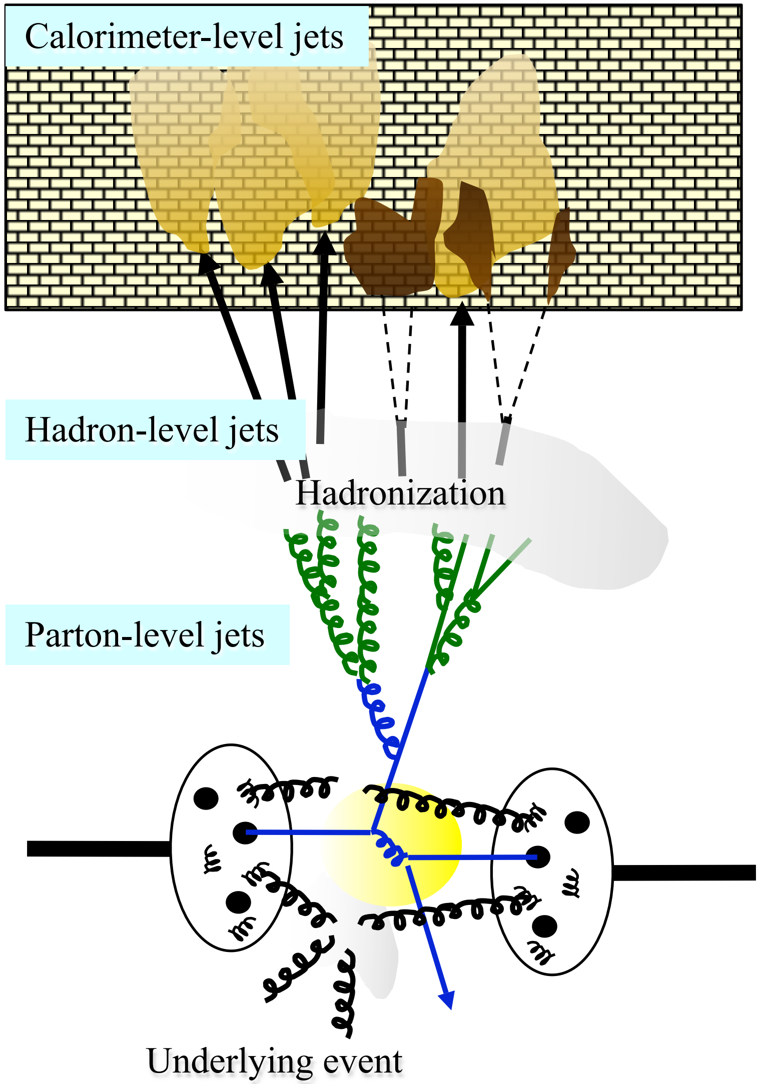
- Data are compared to a variety of QCD calculations (NLO, resummed, leading log Monte Carlo…)

- Dynamics of any new physics will be from QCD...backgrounds to any new physics will be from QCD processes!

CDF High-Mass Dijet Event



Jet Production



Jets are the experimental footprints of quarks and gluons!

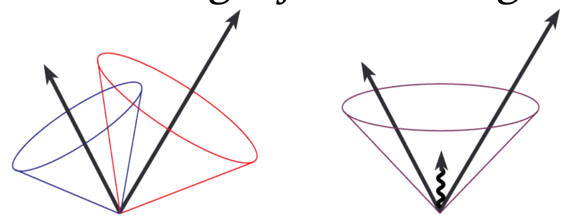
- Jets are collimated sprays of hadrons originating from quarks/gluons from the hard scattering
- Unlike photons and leptons, jets must be defined by an algorithm for quantitative studies
- We need a well-defined algorithm that gives a close relationship between calorimeter-level jets, hadron-level jets, and parton-level jets

Jet Algorithms at CDF

Cone algorithms (JetClu, Midpoint)

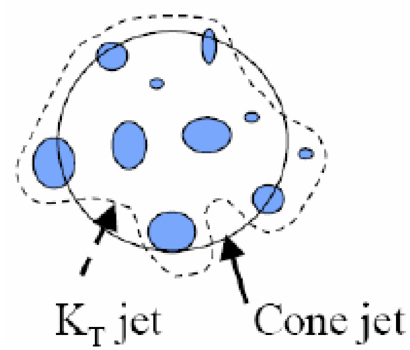
- Cluster objects based on their proximity in y-ϕ (η-ϕ) space
- Starting from seeds (calorimeter towers/particles above threshold), find stable cones (p_T-weighted centroid = geometric center).
- In Run II QCD studies, often use "Midpoint" algorithm, i.e. look for stable cones from middle points between stable cones → Infrared safe to NNLO
- Stable cones sometime overlap → merge cones when overlap > 75%

JetClu is infrared unsafe:
soft parton emission changes jet clustering



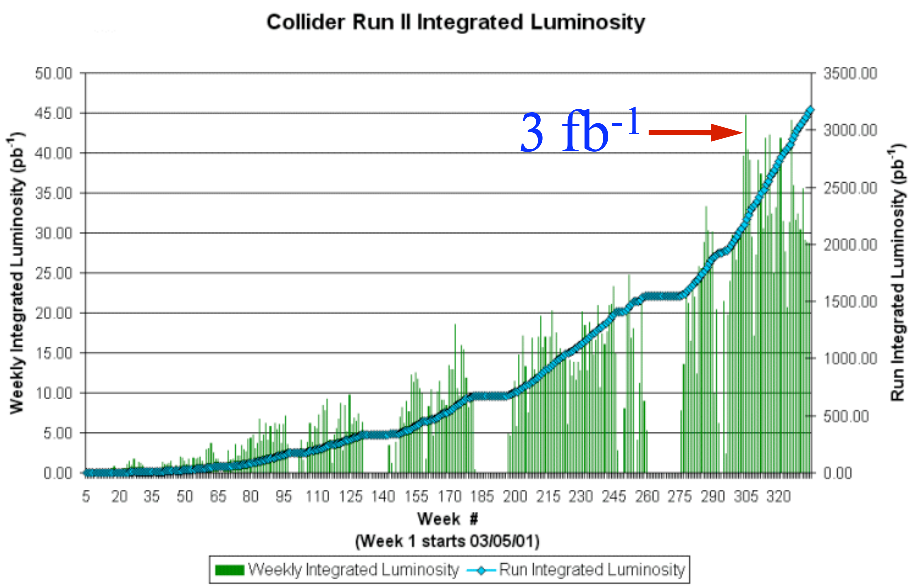
k_T algorithm

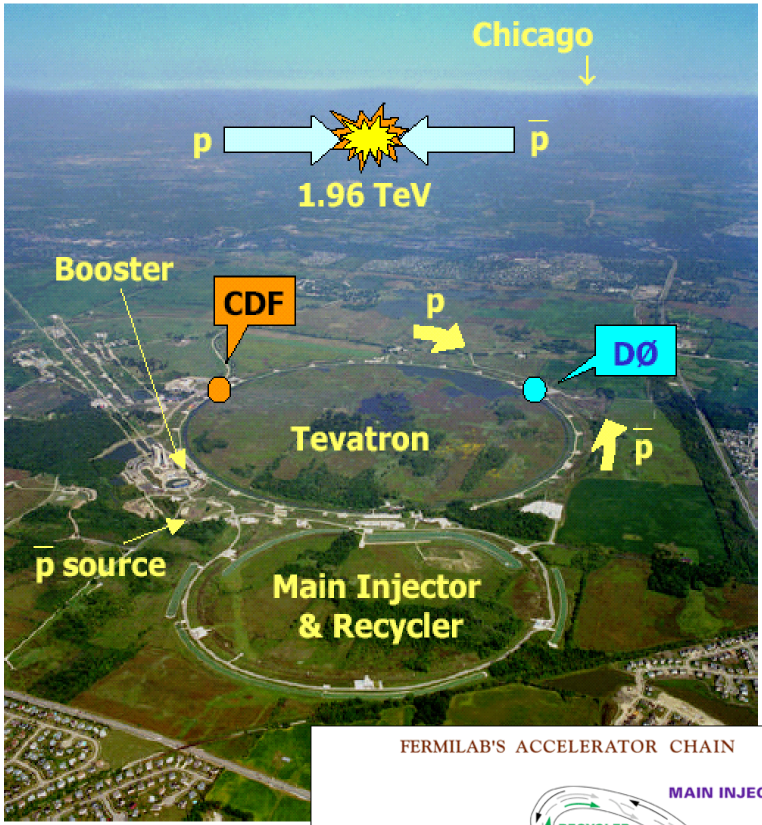
- Cluster objects based on their relative transverse momentum (k_T)
- Iteratively cluster pairs of close objects until all objects become part of jets
- No issue of splitting/merging. Infrared and collinear safe to all orders of QCD.
- Successful at LEP & HERA, but relatively new at the hadron colliders
  - More difficult environment (underlying event, multiple $p\bar{p}$ interactions…)

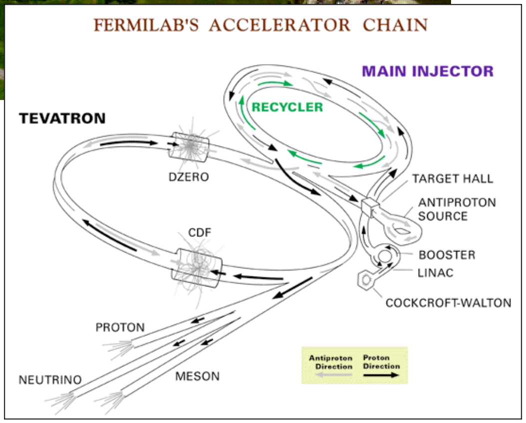


The Fermilab Tevatron — Run 2

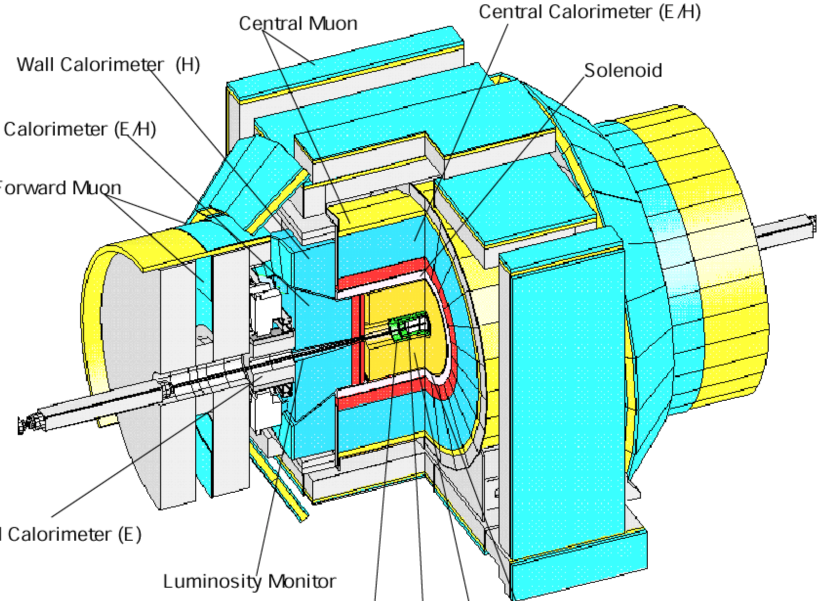
- Proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV
- Run 2 started in March 2001
- Delivered luminosity now > 3 fb^{-1}
- Projection ~6-7 fb^{-1} by 2009







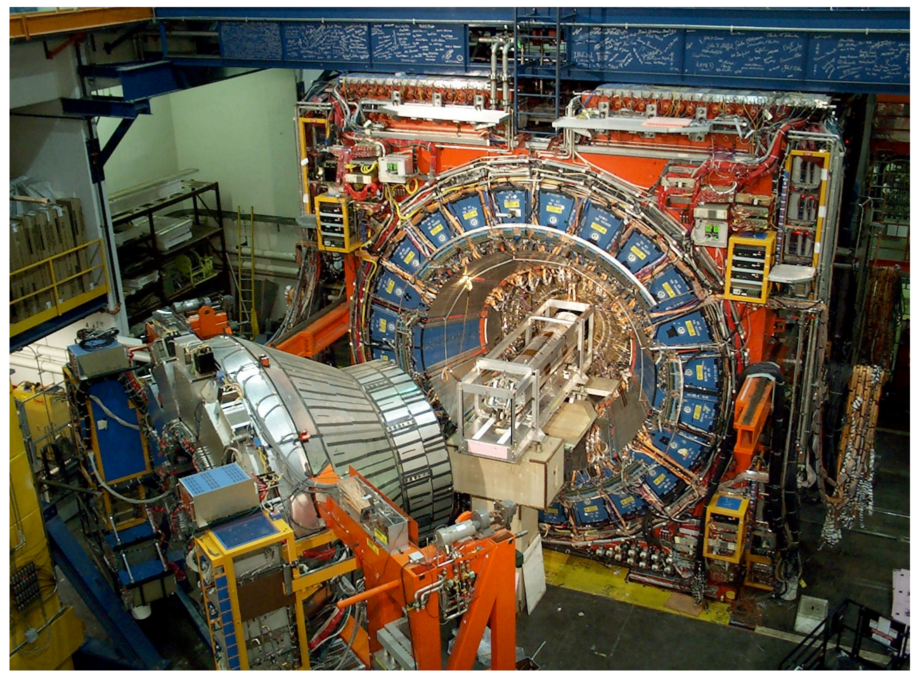
Collider Detector at Fermilab (CDF)



- Data taking efficiency ~ 85%
- About 2.7 fb^{-1} on tape

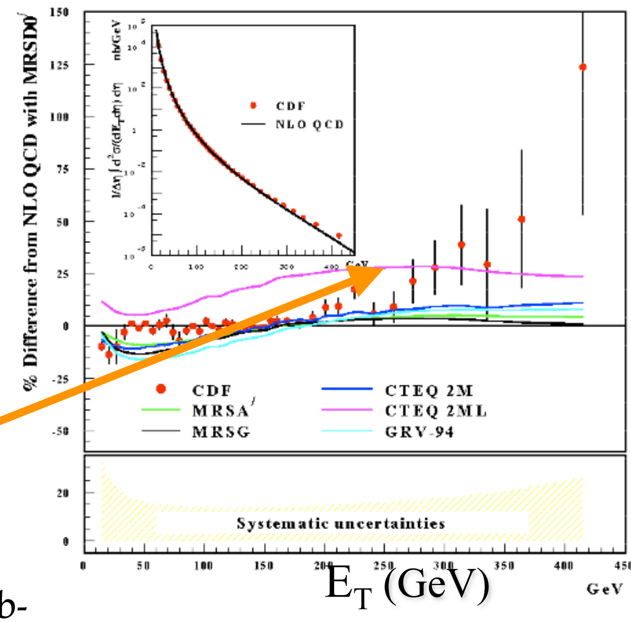
Results shown here use up to 1.7 fb^{-1}

- CDF — A Multi-purpose Detector
  - Silicon vertex detector
  - Central drift chamber (COT)
  - Solenoid magnet
  - EM and hadron calorimeters
  - Muon chambers

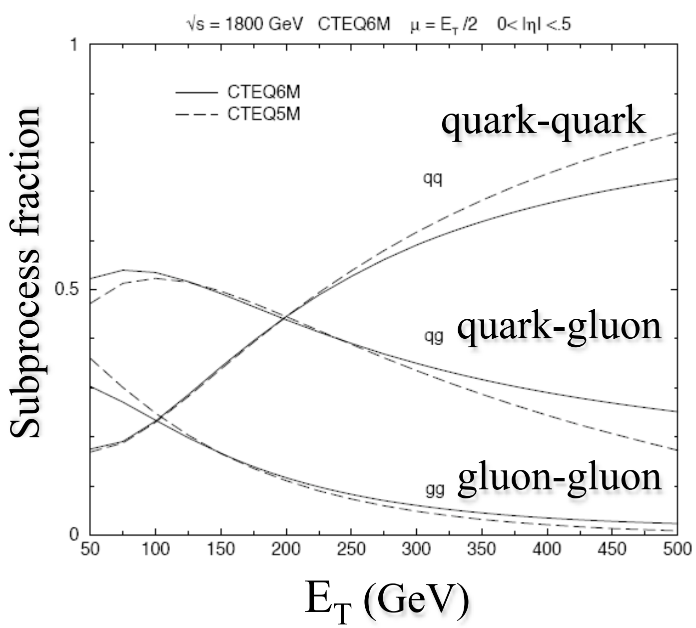


Inclusive Jet Production

- Test perturbative QCD predictions over ~8 orders of magnitude in cross section
- Constrain QCD parameters (PDF, α_s)
- Potentially sensitive to new physics
  - Probing distances ~10^{-19} m

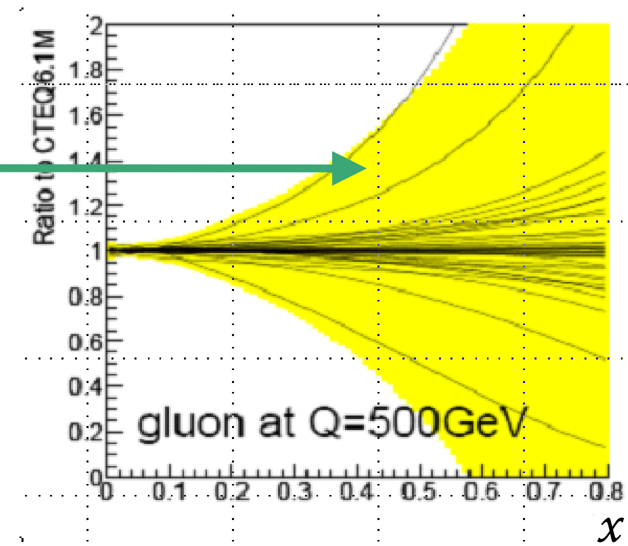


Excitement (?) 10 years ago



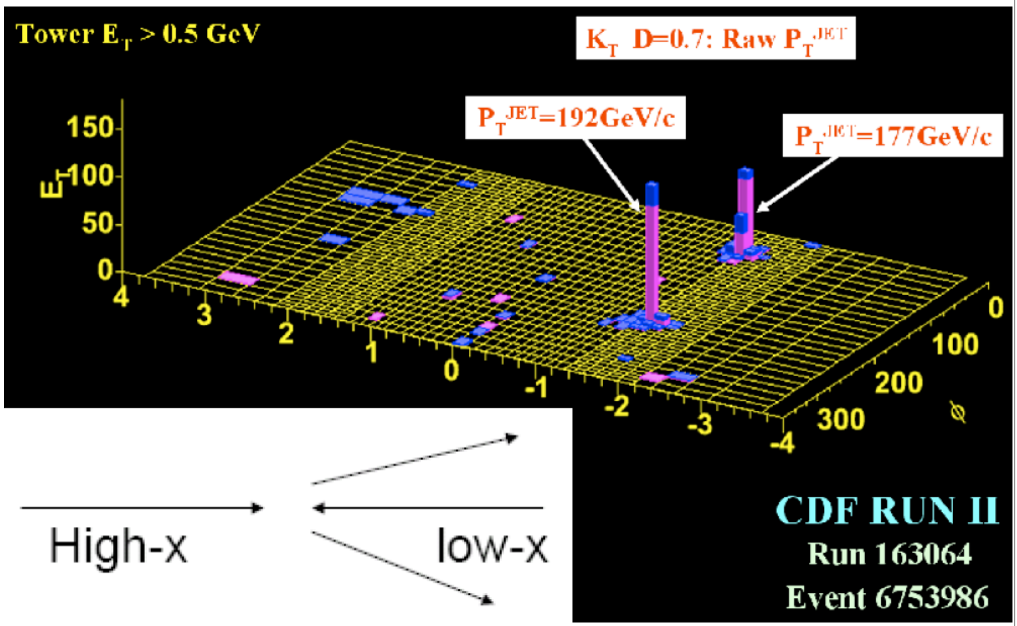
Sizable cross section from quark-gluon sub-process

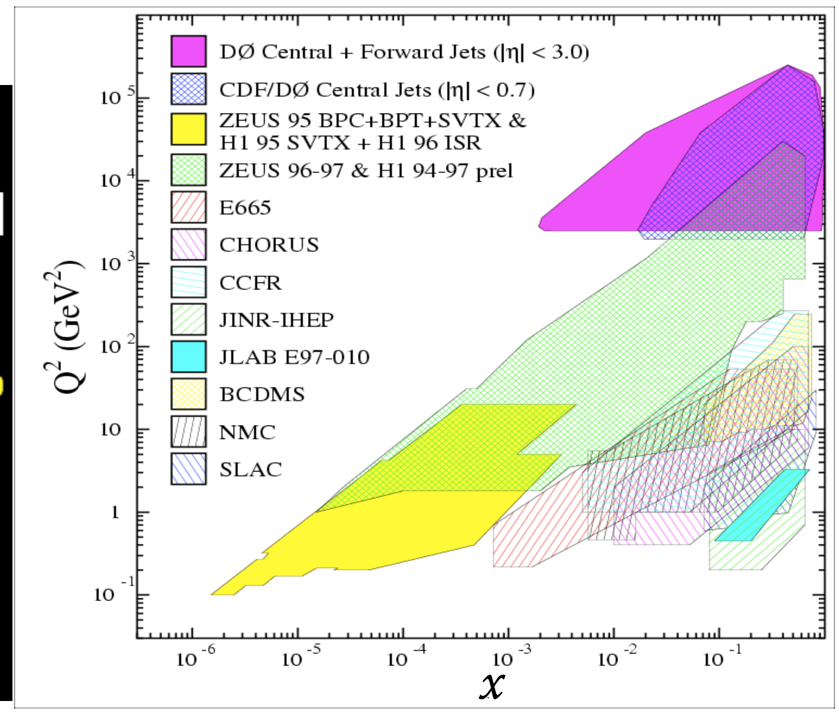
High-x gluon not well known...can be accommodated by the Standard Model



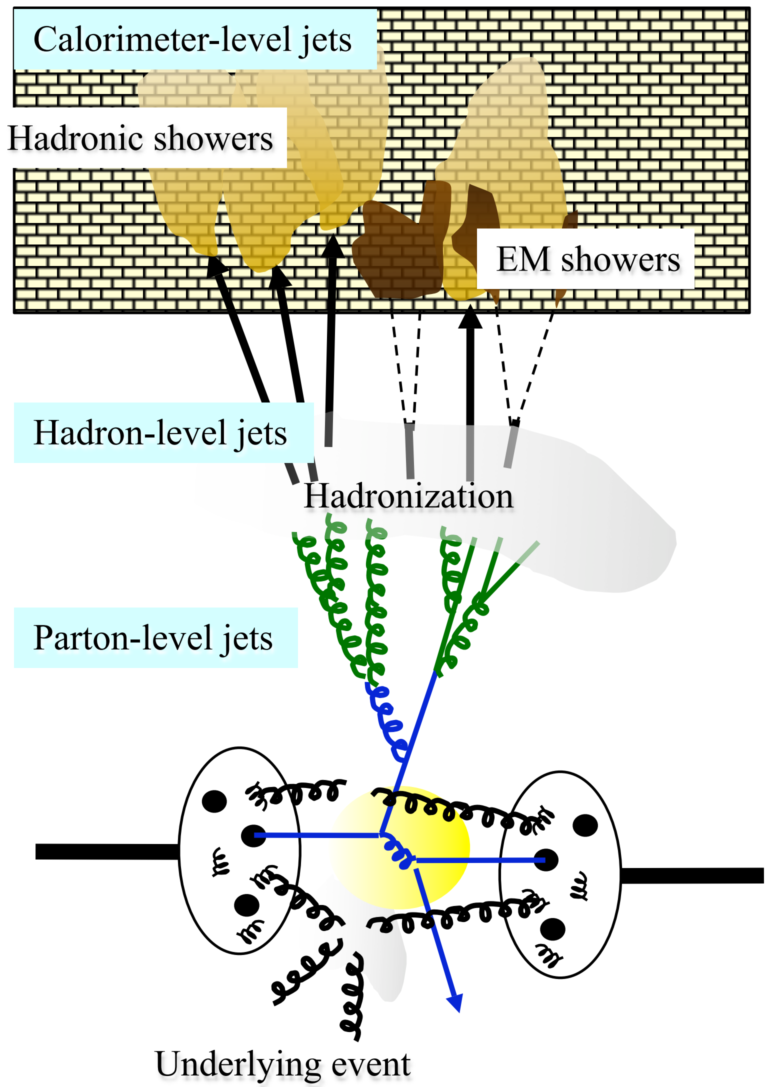
Forward Jet Measurement

- Forward jets probe high-x at lower Q^2 ($= -q^2$) than central jets
  - Q^2 evolution given by DGLAP
  - Essential to distinguish PDF and possible new physics at higher Q^2
- Also, extend the sensitivity to lower x





Jet Energy Corrections



Measure calorimeter-level jets.
Then, correct for:

- Energy from additional $p\bar{p}$ collisions
- Calorimeter non-uniformity
- Average energy loss and smearing effect in calorimeter energy measurement
  - Shower simulation tuned to data

➡ Hadron-level jet cross section

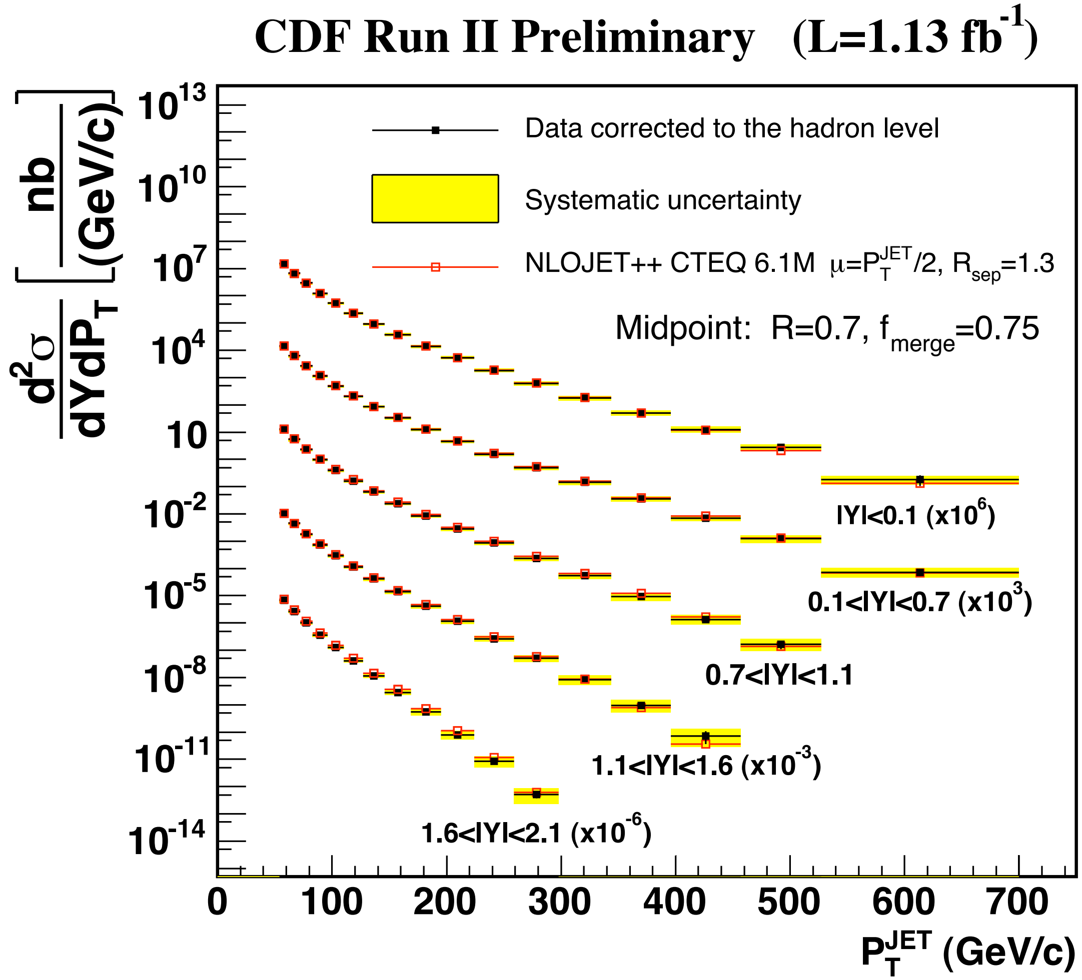
To make fair comparisons with parton-level pQCD predictions, need to account for:

- Underlying event
- Hadronization

Effects evaluated from simulated jet events.
Underlying event in MC is tuned to data.

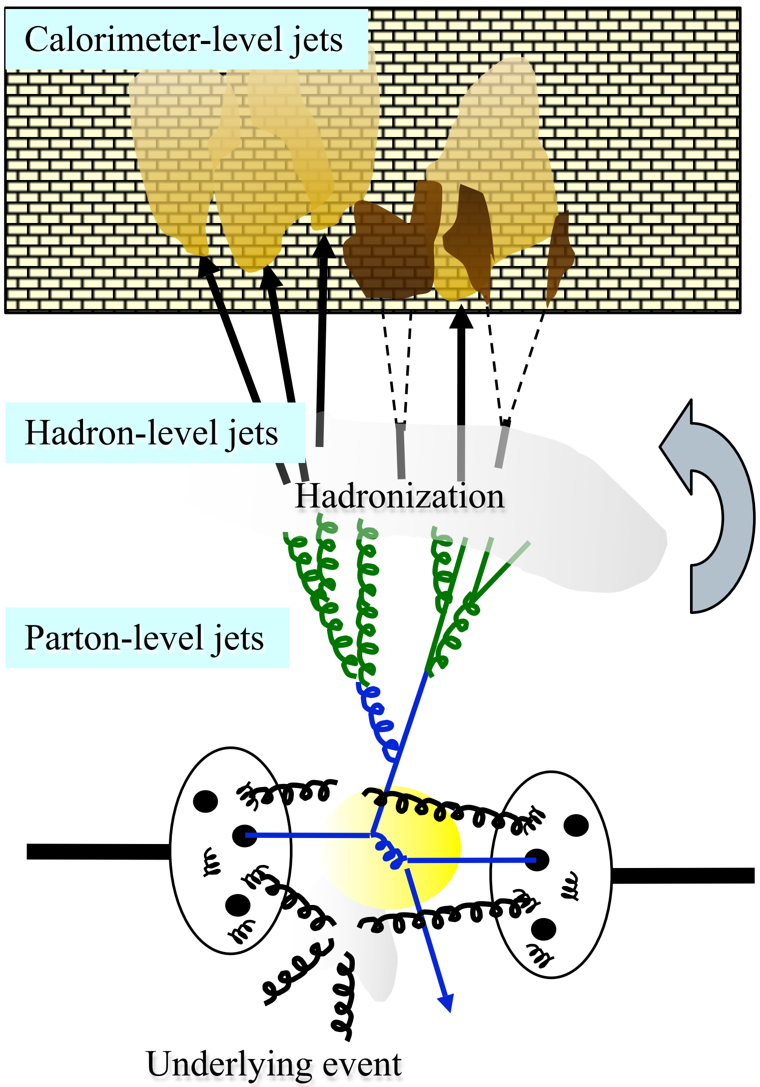
Inclusive Jets with Midpoint

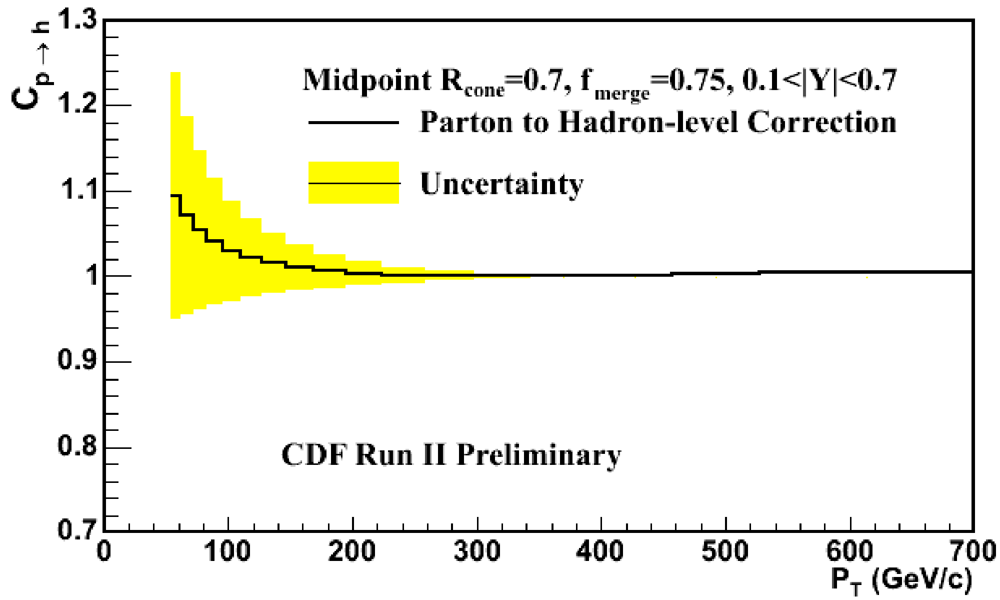
- L = 1.13 fb^{-1}
- Jets reconstructed with Midpoint algorithm, R = 0.7
- Consistent with NLO pQCD predictions
  - Experimental uncertainties dominated by jet energy scale (2-3%)
  - Theoretical uncertainties mainly from PDF (gluon at high x)



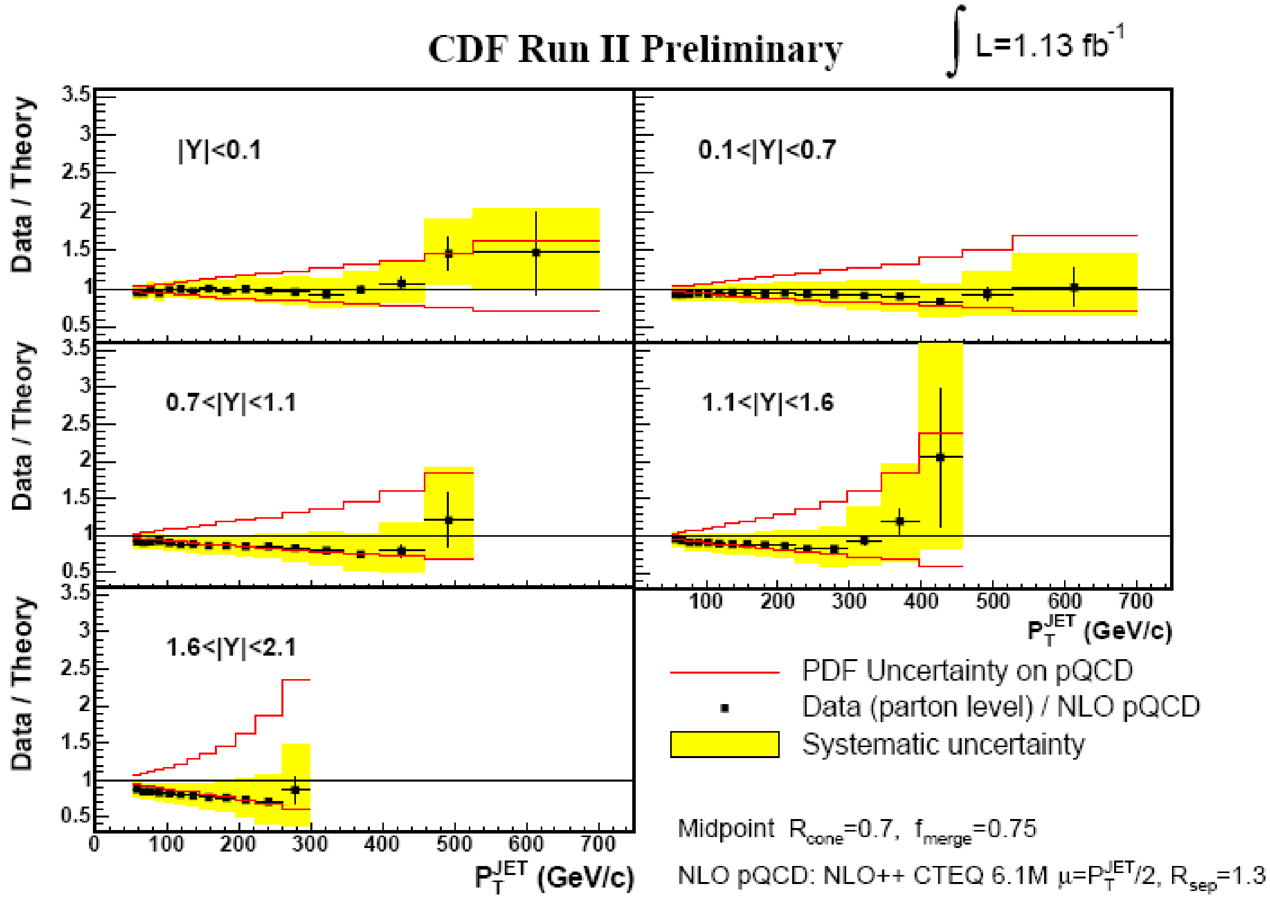
(6% luminosity uncertainty not included)

Underlying Event & Hadronization



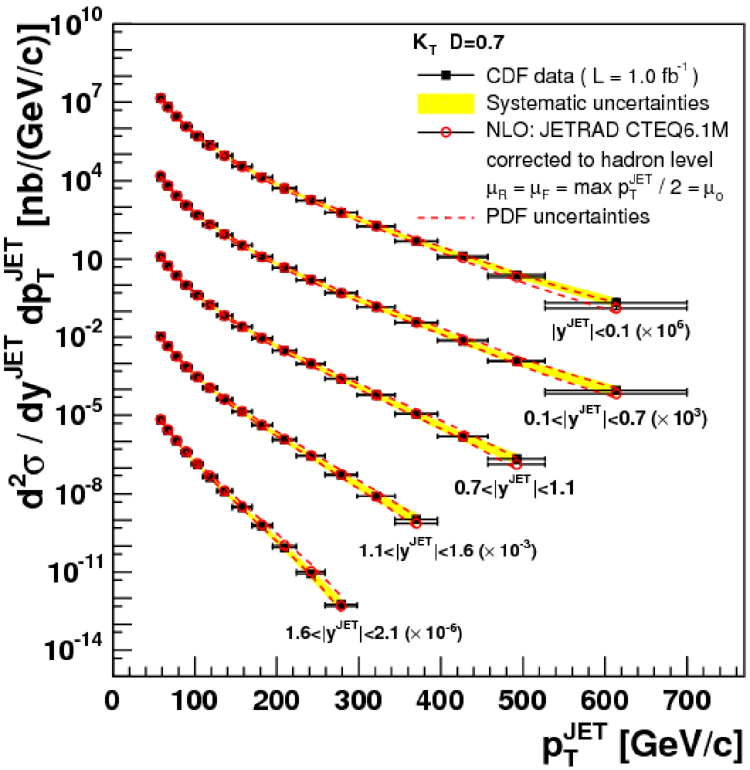


Inclusive Jet Production with Midpoint



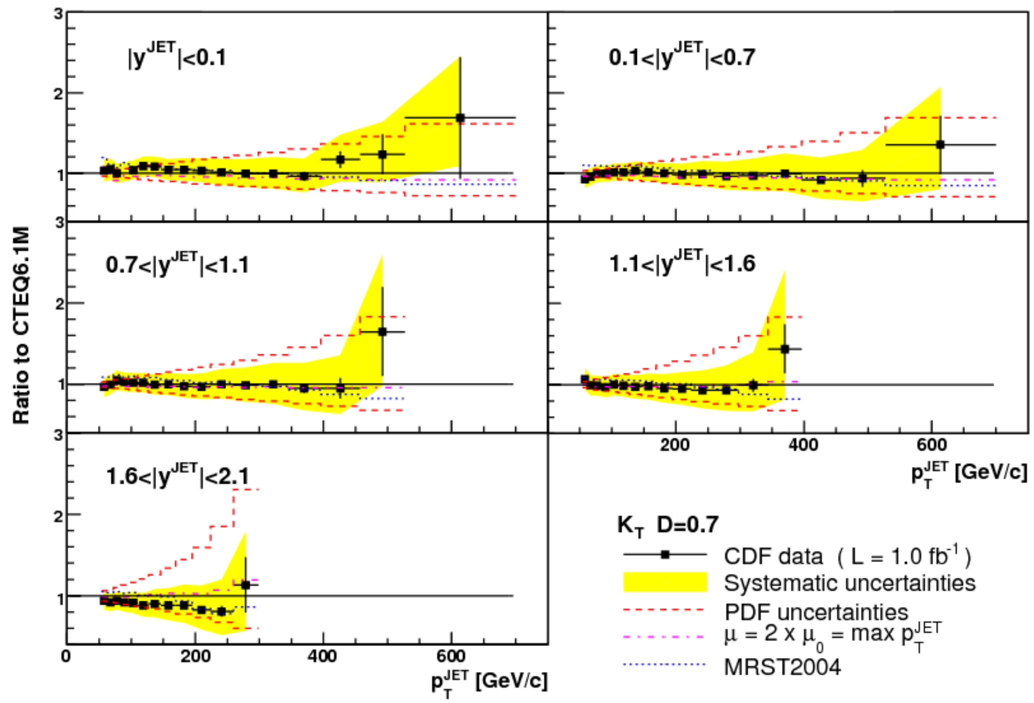
- Data consistent with NLO pQCD predictions in all rapidity regions
- Experimental uncertainty in the forward region smaller than the PDF
  - will contribute to further constrain PDFs

Inclusive Jets with k_T Algorithm



- L = 1.0 fb^{-1}
- Jets reconstructed with the k_T algorithm, *D*= 0.7.

D is the separation parameter which characterizes the size of the jets



Again, data in good agreement with NLO pQCD predictions

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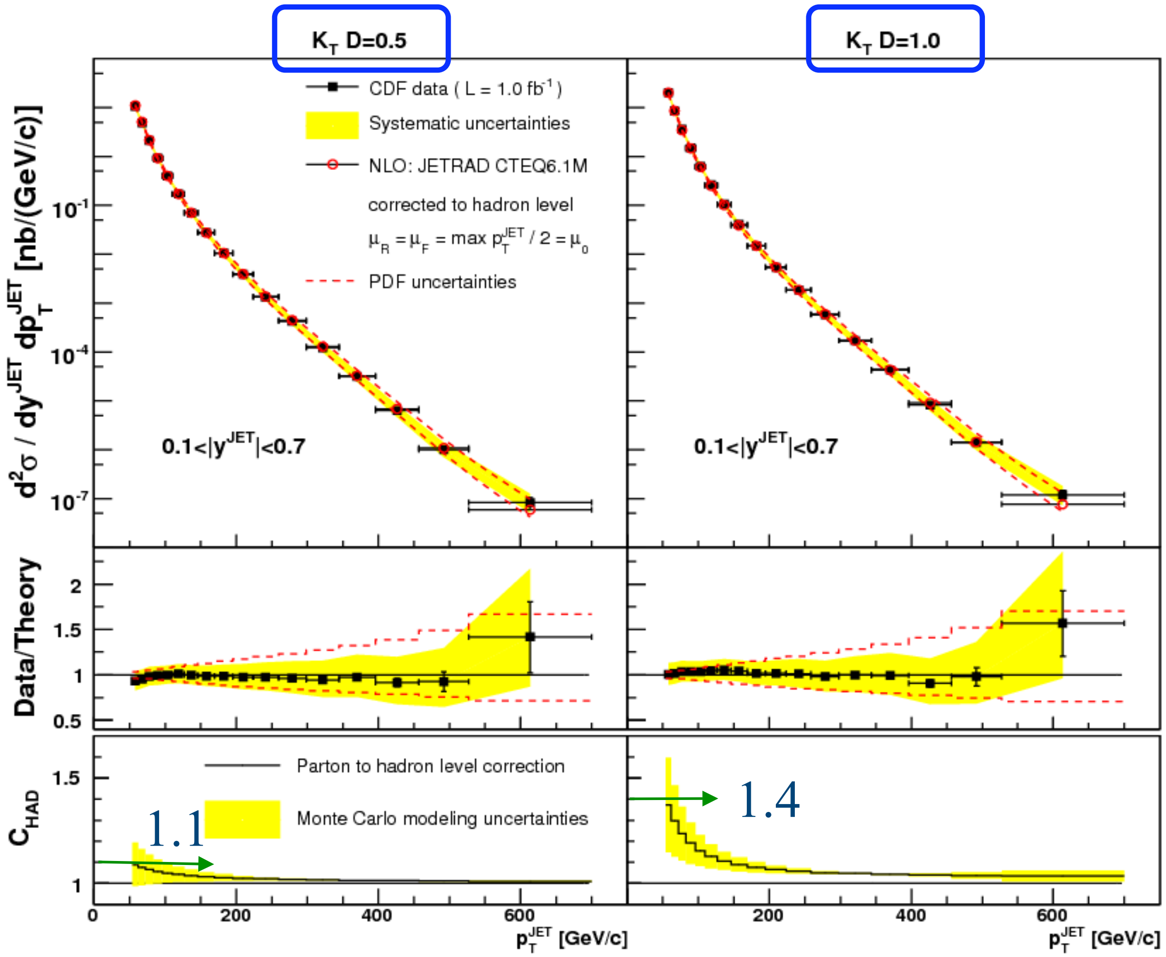
Inclusive Jets with k_T vs. D

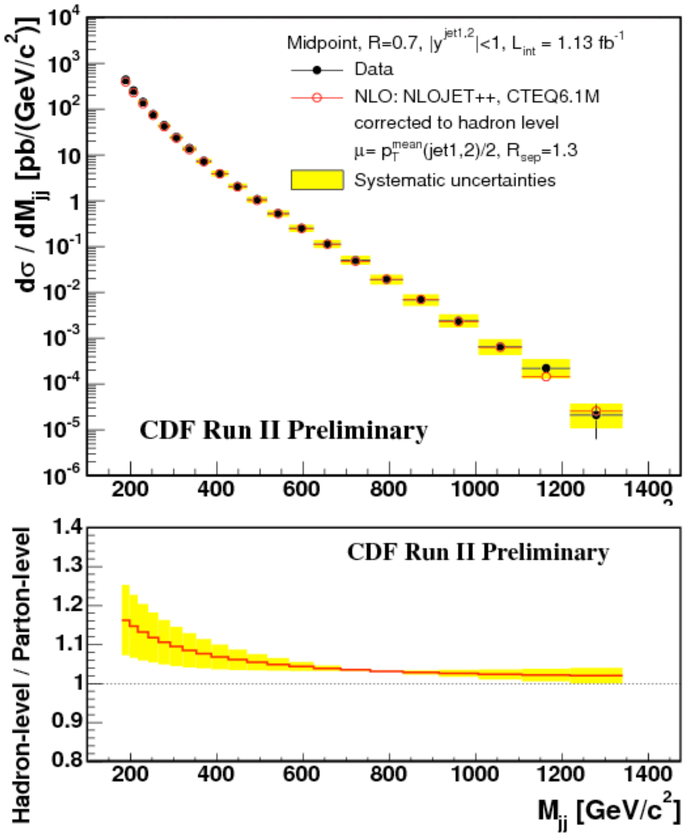


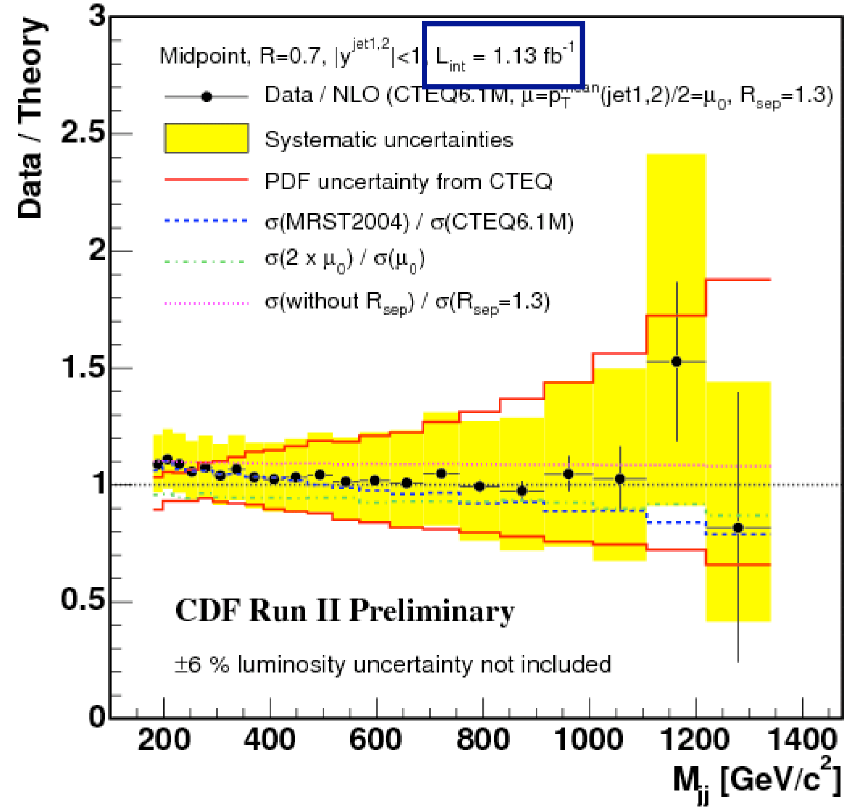
- Measurement with different *D* parameters
- Parton-to-hadron level corrections larger for larger *D* parameters (larger UE contributions)
- Both measurements in good agreement with NLO pQCD after UE and hadronization corrections

➡ NLO pQCD provides a reasonable description of dependence on jet size.

Dijet Production

- Test of pQCD predictions
- Sensitive to new physics:
  decays of massive particles,
  compositeness



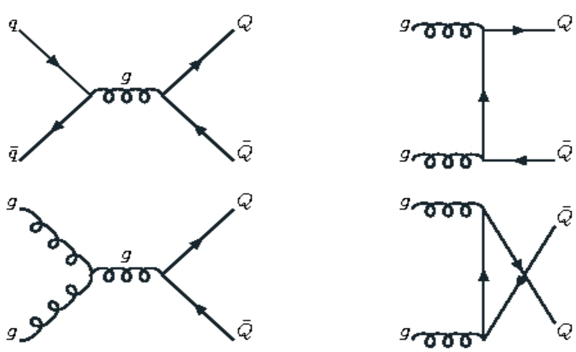


- Consistent with NLO pQCD predictions
  - Experimental uncertainties comparable to PDF uncertainties
- Limits on new physics being worked out…

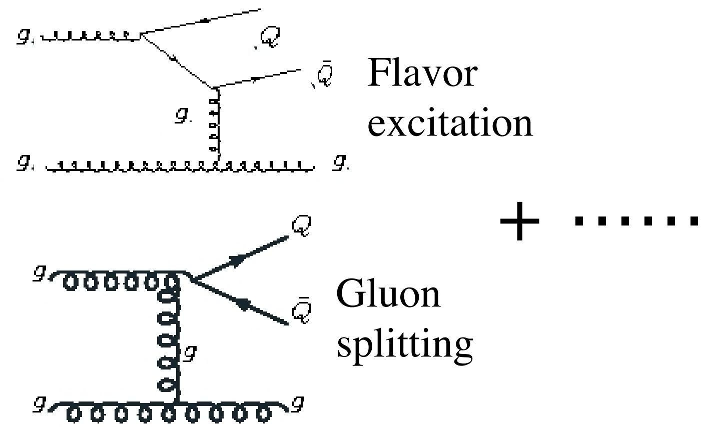
b-jet Production

- *b*-jets are signatures of many important and possible new physics processes.
- Understanding *b*-jet production has been a big challenge in QCD.
  - Only recently, data and theory started to show agreement; more precise measurements, fixed order + NLL, improved fragmentation function, PDFs

Flavor creation



Leading order processes



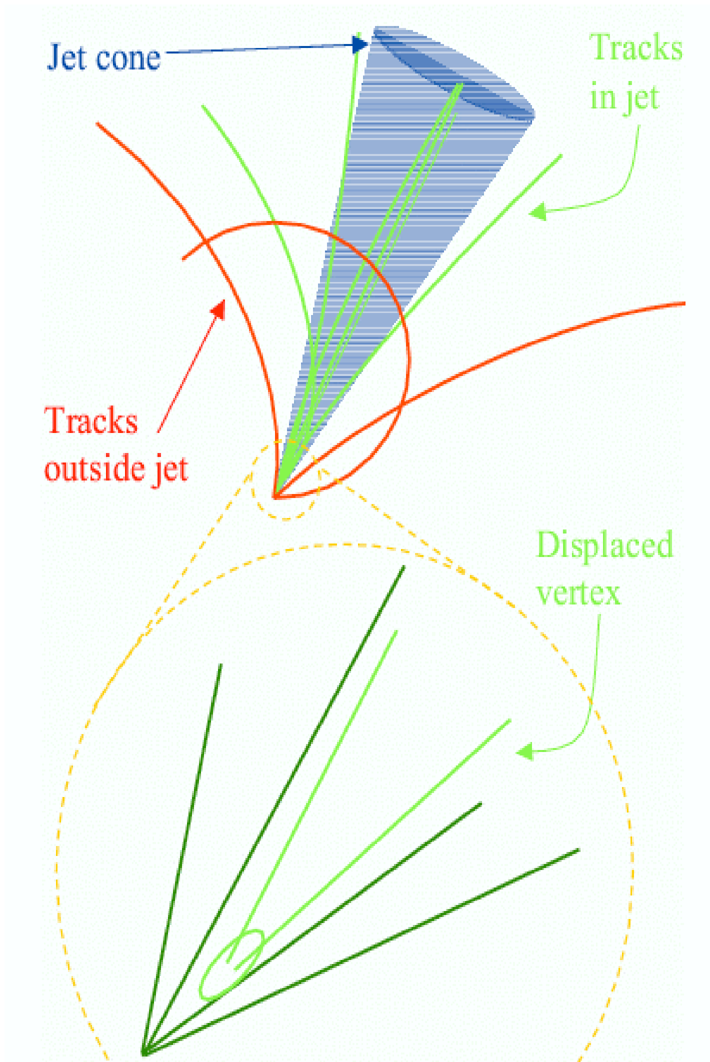
Next-to-leading order processes

- Measurement on $b\bar{b}$ dijet production is sensitive to different production mechanisms:
  - Flavor creation at high $\Delta\phi$
  - Flavor excitation or gluon splitting at low $\Delta\phi$

b-jet Identification

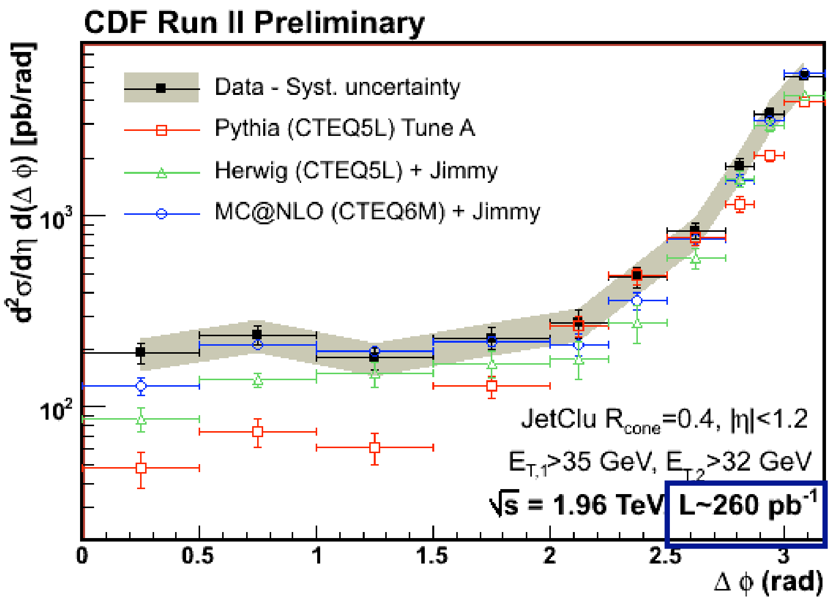
The most commonly used "tagging" technique at CDF identifies *b*-jets with a displaced secondary vertex (long *B* hadron lifetime, cτ ~ 450 μm)

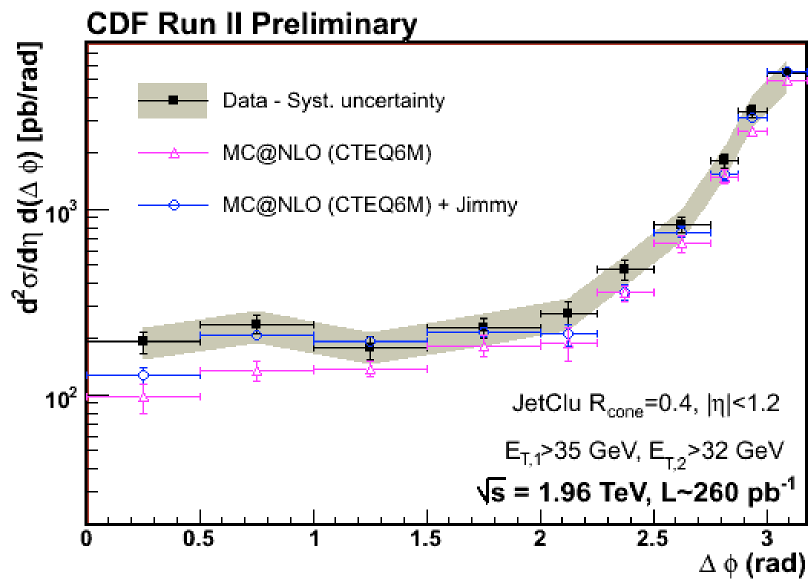
- consider tracks in η-φ cone of 0.4 around jet axis
- reconstruct secondary vertex from displaced tracks
- If the vertex has large transverse displacement (Lxy), the jet is "*b*-tagged"



$b\bar{b}$ Dijet Production

- *b*-jets selection using secondary vertex tagging both at the trigger and offline levels
- Comparisons with LO MC (Pythia and Herwig) and NLO MC (MC@NLO with/without Jimmy for multiple parton interactions)

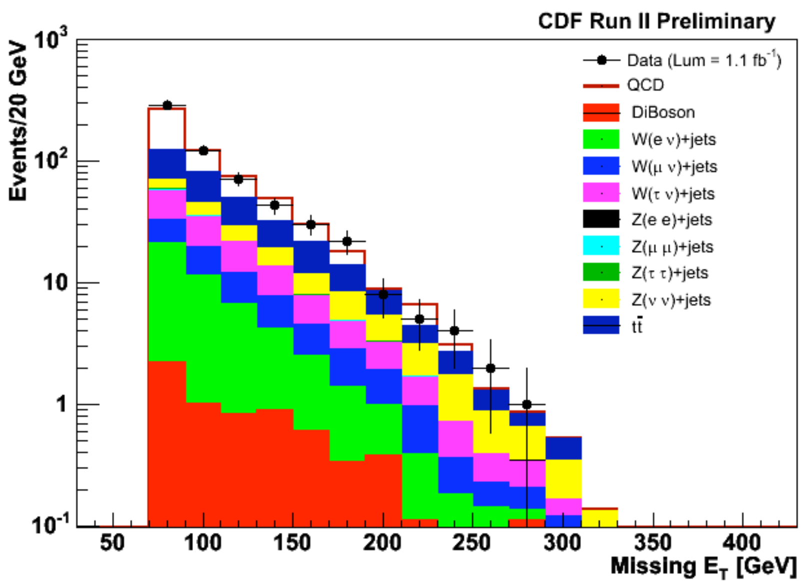




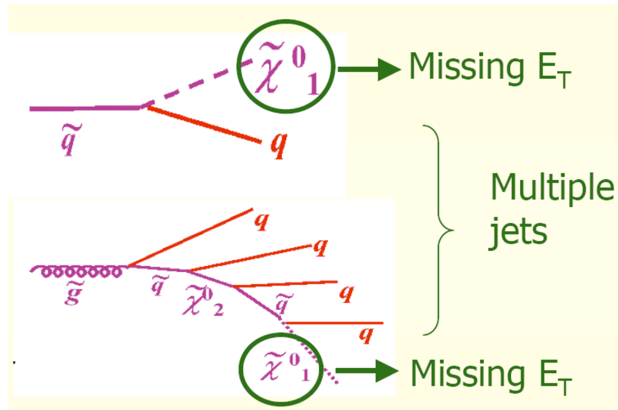
- MC@NLO reproduces data within errors
  (at low $\Delta\phi$, MC@NLO> Herwig > Pythia)
- Simulation of underlying event (Jimmy) improves data-theory agreement

Vector Boson + Jet Production

- Test of pQCD at high Q^2
- Important for many physics searches



SUSY searches in the missing E_T + Jets channel



Major backgrounds

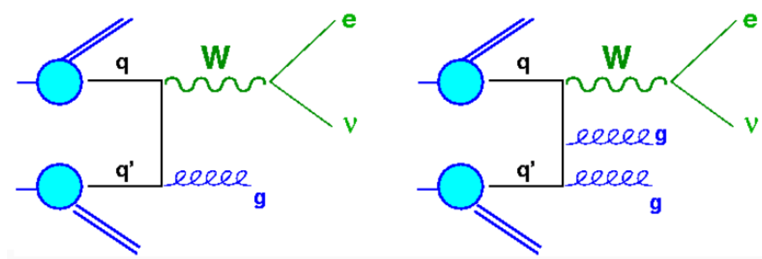
- $Z \rightarrow \nu\nu$ + jets
- $W \rightarrow l\nu$ + jets
- QCD, Top, WW…

Crucial to understand boson-jets production!

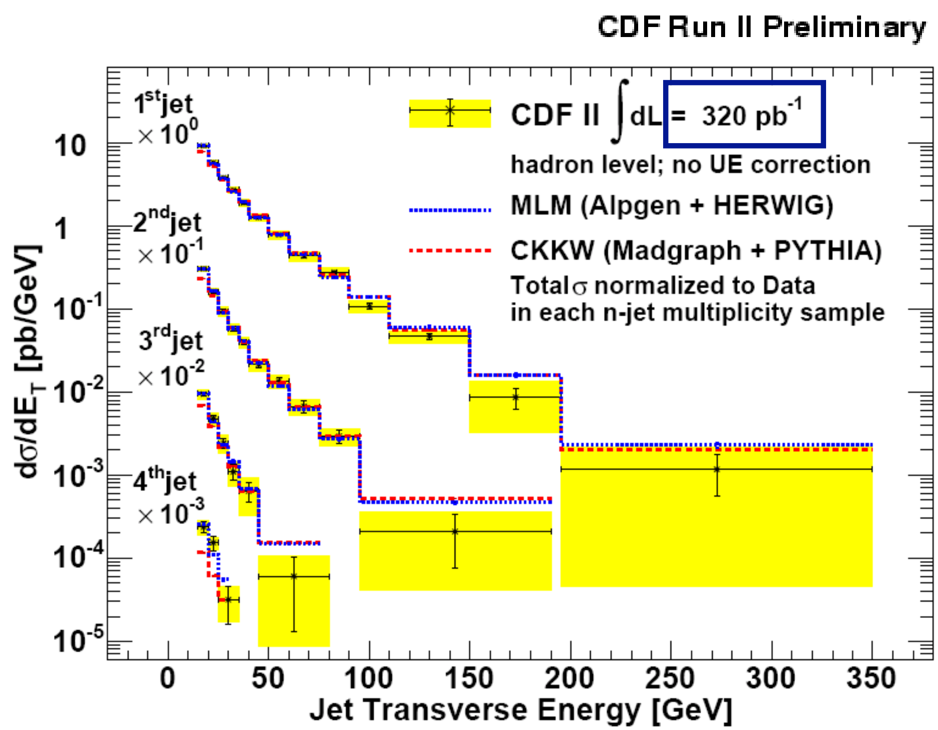
W + Jets Production

- W events selected with electron + missing E_T ($W \rightarrow e\nu$)
- Jets clustered with JetClu R=0.4
  $E_T^{jet} > 15$ GeV ; $|y^{jet}| < 2$.
- Compare with matrix element + parton shower (ME+PS) Monte Carlo predictions
  - Special ME-PS matching (MLM, CKKW) to avoid double counting
  - Comparisons in shape only

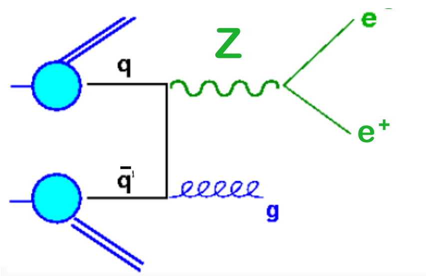
Reasonable agreement with ME+PS MC predictions



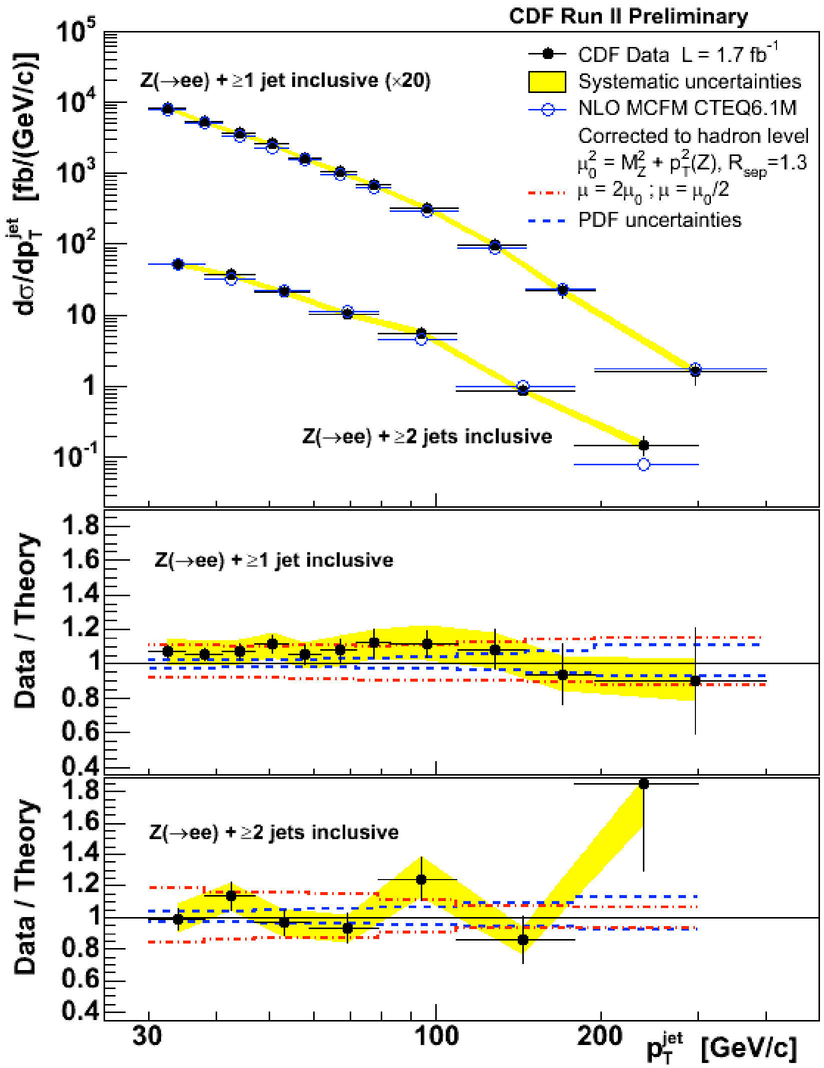
... + parton showers



Z + Jets Production

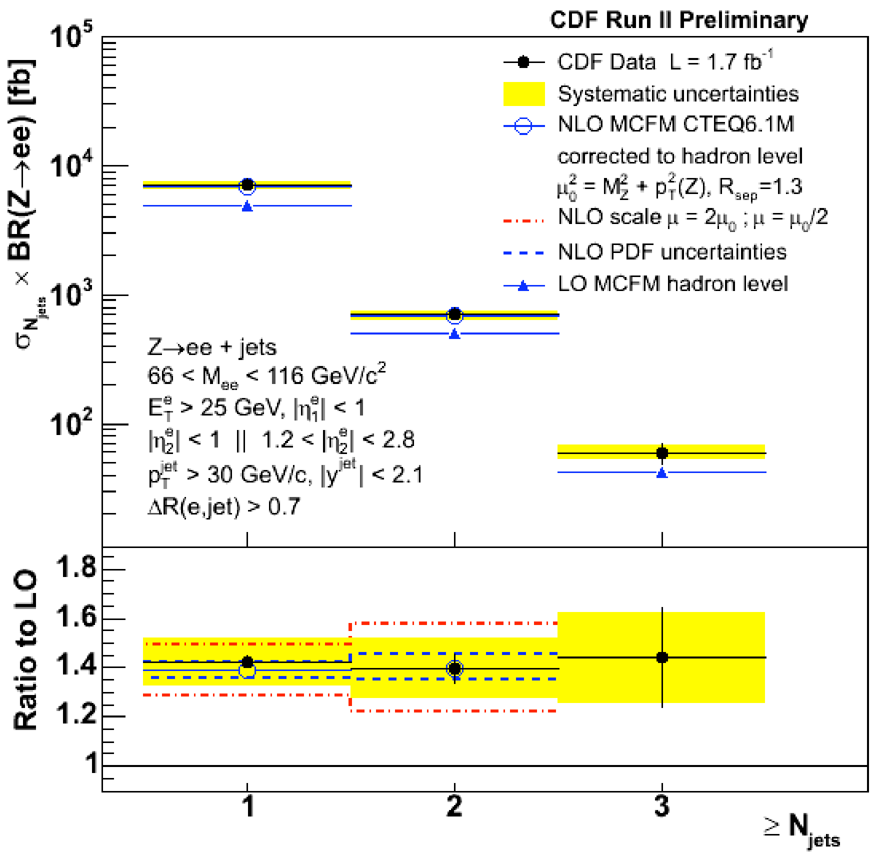


- $L = 1.7\ fb^{-1}$
- Z events selected with di-electrons
- Jets clustered with Midpoint algorithm R=0.7,
  $p_T^{jet} > 30$ GeV ; $|y^{jet}| < 2.1$.



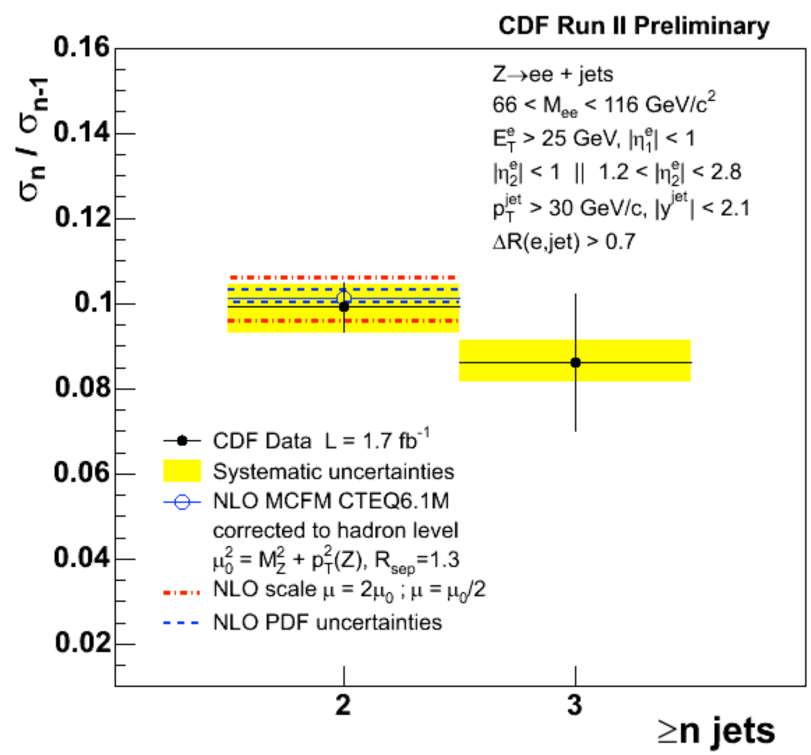
Good agreement with NLO pQCD predictions

Z + Jets Production



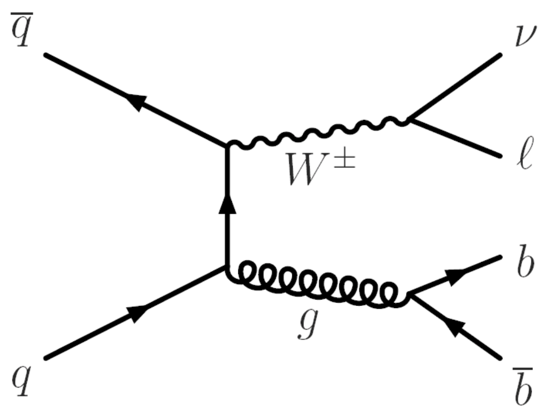
- Data/LO and NLO/LO ratios ~ constant

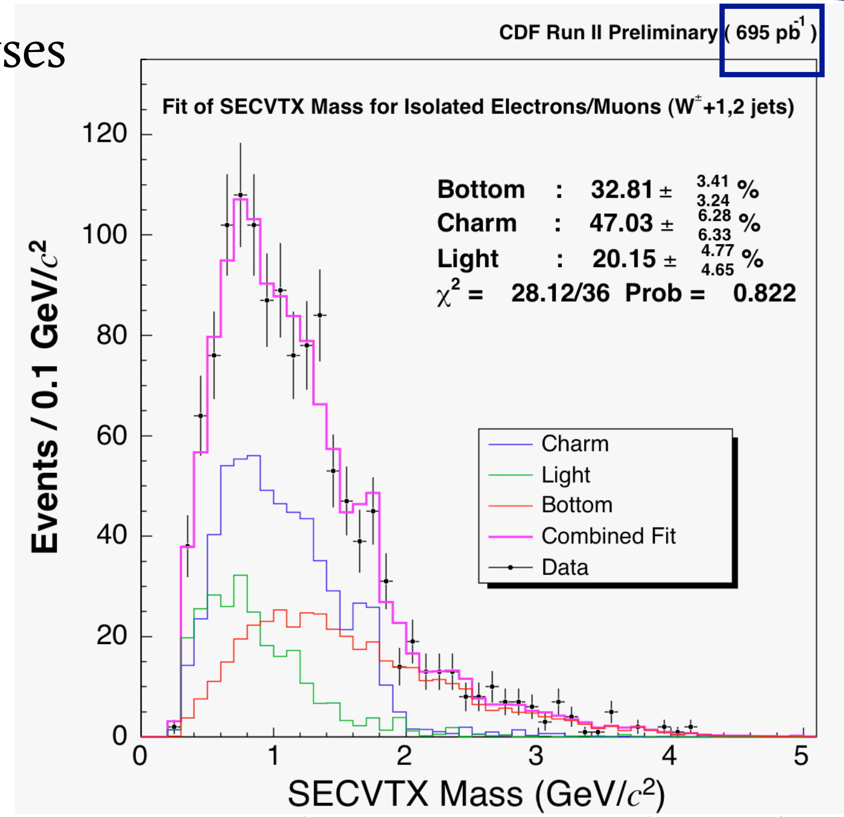
- Ratio of $\sigma(n)/\sigma(n-1) \sim \alpha_s$



W + $b\bar{b}$ Production

- Large background for many analyses
  - SM Higgs (WH) production
  - Single top quark production
  - $t\bar{t}$ production





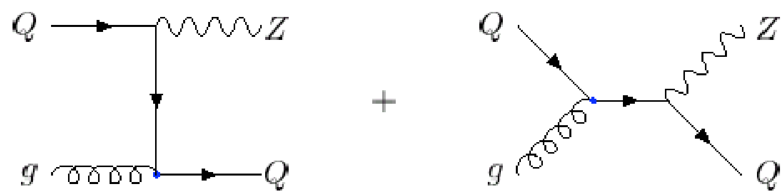
In secondary-vertex-tagged sample, fit for light, c, b contributions.

$$\boxed{\sigma(W^{\pm} \to b\bar{b}) \times \mathrm{BR}(W^{\pm} \to \ell^{\pm}\nu) = 0.90 \pm 0.20 \ (\mathrm{stat.}) \pm 0.26 \ (\mathrm{syst.}) \ \mathrm{pb}}$$

$(E_T^{\mathrm{jet}} > 20 \ \mathrm{GeV}, |\eta^{\mathrm{jet}}| < 2)$

Alpgen predictions: (0.74 ± 0.18 pb)

Z + *b* Jets Production

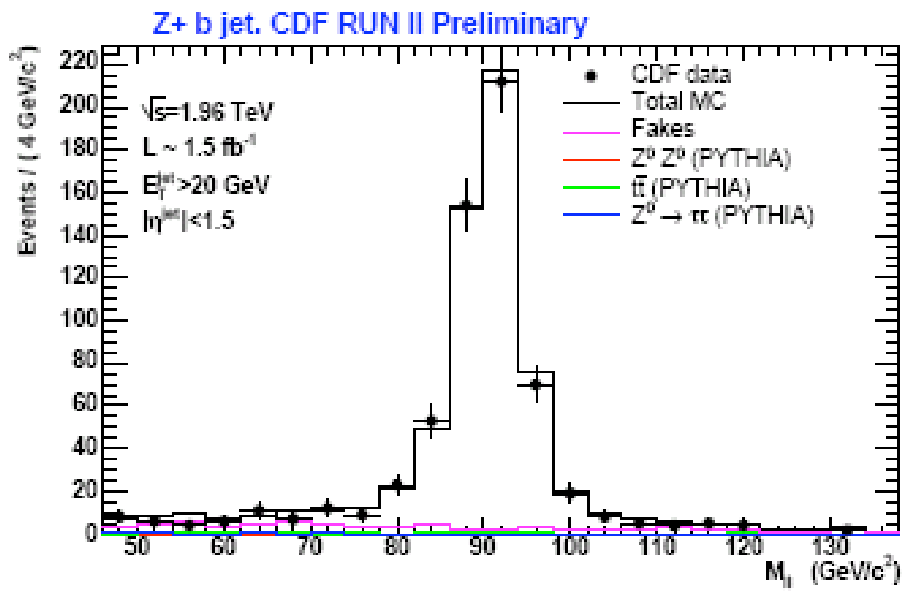


Probe the less-well-known heavy flavor content of the proton. Important for

- Single top: $qb \to q't$ and $gb \to Wt$
- SUSY higgs: $gb \to hb$, $bb \to h$

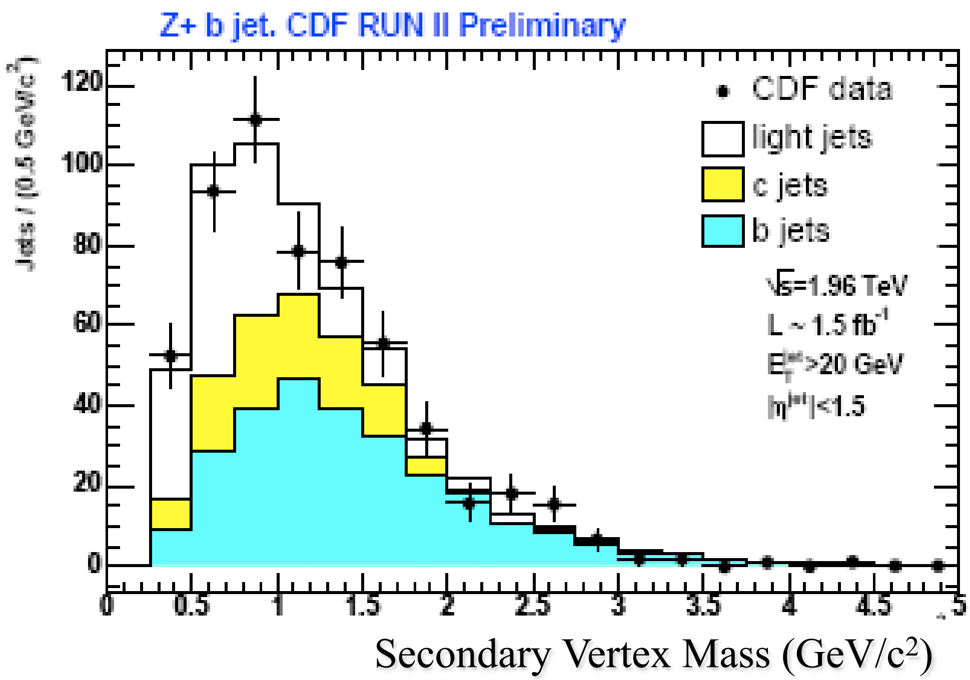
Major background for SM Higgs searches (ZH, H → $b\bar{b}$)

- L = 1.5 fb^{-1}
- Z events selected with di-leptons (ee and μμ).
- Jets clustered with a cone algorithm R=0.7
- *b*-jet identification: secondary vertex tagging



Z + *b* Jets Production

b, c and light fractions determined from the template fit of the secondary vertex mass distributions

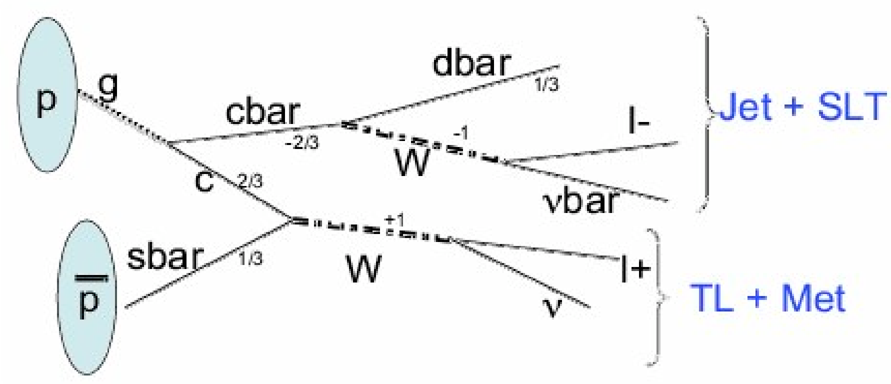


E_T^{jet}>20 GeV, $\lvert\eta^{jet}\rvert$<1.5 R_{jet}=0.7	CDF Run II Preliminary measurement	PYTHIA	MCFM NLO	MCFM NLO + UE + hadr.
σ(Z+*b*-jet)	0.94 ± 0.15 ± 0.15 (pb)		0.51 pb	0.56 (pb)
σ(Z+*b*-jet) / σ(Z)	0. 369 ± 0.057 ± 0.055 %	0.35 %	0.21 %	0.23 %
σ(Z+*b*-jet) / σ(Z+jet)	2.35 ± 0.36 ± 0.45 %	2.18 %	1.88 %	1.77 %

Data somewhat higher than NLO predictions. Theorists contacted for further investigation.

W + charm Production

- First measurement of the *Wc* production cross section!
- The technique uses soft muon flavor tagging, where we identify jets with a muon from the semileptonic decay of the candidate *c*-quark. (Jet E_T > 10 GeV)
- W events are selected with e/μ + missing E_T (> 25 GeV)
- We study the charge correlation of the *W* boson with the muon. Candidate events are fully anti-correlated!



g+s : ~ 90%, g+d: 10%

Number of events with at least one SLT-tagged jet:

	W + 1 jet	W + 2 jets
$W \to e\nu$	725	360
$W \to \mu\nu$	491	246

W + charm Production

- The Wc production cross section is obtained using:

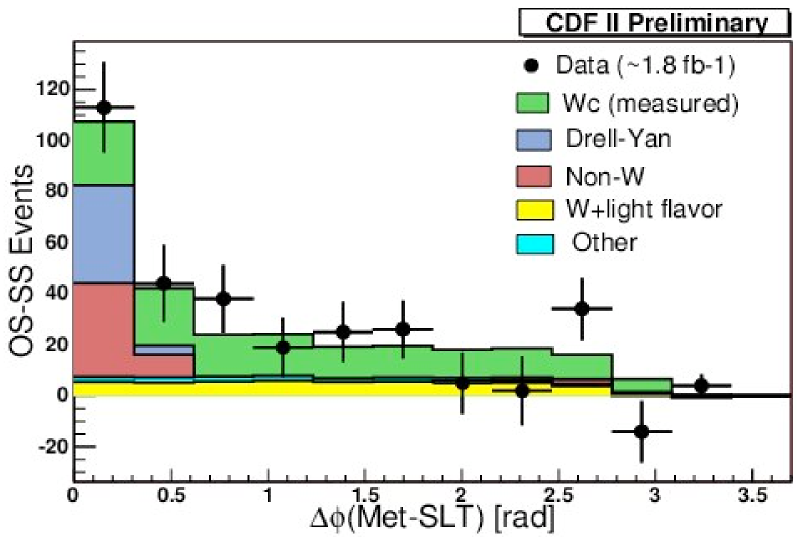
$$\sigma_{Wc} = \frac{N^{OS-SS}_{\mathrm{tot}} - N^{OS-SS}_{\mathrm{bkg}}}{Acc \cdot \int L}$$

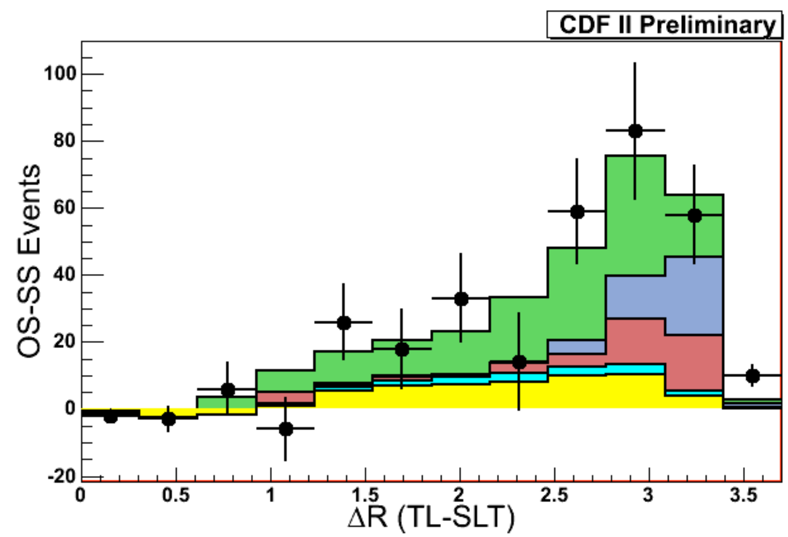
- backgrounds are
  - W+light flavor
  - non-W QCD
  - Drell-Yan
  - etc

- Cross section measurement:

$$\boxed{\sigma_{Wc} \times BR(W \to \ell\nu) = 28.5 \pm 8.2\ (\mathrm{stat})\ {}^{+4.0}_{-4.3}\ (\mathrm{syst}) \pm 1.7\ (\mathrm{lum})\ \mathrm{pb}}$$

where $p_T(c) > 8\ \mathrm{GeV}/c$ and $|\eta_c| < 3.0$ L = 1.8 fb^{-1}





Conclusions

CDF has a broad program on jet physics which is making a significant impact on better understanding of jet production mechanisms and QCD.

- Inclusive jets, dijets, $b\bar{b}$ dijets, boson + jets, boson + b-jets, W + charm
- Providing stringent tests of QCD calculations and further constraints on QCD parameters
  - NLO pQCD calculations, ME-PS matching techniques
  - Proton PDFs (especially high-x gluons)
- QCD processes often the most important background to electroweak and possible new physics processes
  - ➡ Better understanding will enhance the potential for new physics discoveries at the Tevatron and also at the upcoming LHC!

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